Magnetic Forces on Ferromagnetic Objects

Ferromagnetic objects can experience rotational and translational forces when immersed in a magnetic field. These forces can increase the risk of accidents associated with the use of common work materials (such as tools, carts, gas cylinders, and safety shoes) as well as medical complications (such as the dislodging of aneurysm clips). Following are mathematical descriptions of the forces. The model is complicated and is provided for reference purposes only. It should be noted that the model assumes that the ferromagnetic object is a sphere. It should be noted that assumptions for the shape and size of the object could cause a large underestimation of results (the difference between the forces on a sphere and a long cylindrical soft iron rod is on the order of 1,000). It is recommended that experimenters use one of the following methods to estimate forces on ferromagnetic objects.

- Use a physical device (e.g. a small-scale model) of a typical object to actually determine the effects on the object. Select an object which takes into account the size and type of material to be used in the field.
- Use a model simulation program such as
  (a) Poisson for 2-dimensional models, or
  (b) TOSCA for 3-dimensional models.
  These programs take into account force variations due to size and type of material.

Small ferromagnetic objects, such as paper clips or washers hung from a string, can be used to indicate the presence of a field, but it must be determined separately if any hazards to personnel or equipment can result. Care should be taken in choosing the shape and size of the object (higher length-to-diameter ratio and/or the higher ferromagnetic property of the material will result in a stronger magnetic force). Any test procedures should be reviewed for safety prior to being performed.

Fermi Laboratory Background Information

Rotational Force

The torque experienced by a ferromagnetic object depends on the magnetic field strength:

$$L_{mag} = -mH \sin\phi$$

Where L_{mag} = torque experienced by the ferromagnetic object (N-m)
m = magnetic moment of the ferromagnetic object (Wb-m)
H = magnetic field density (A/m)
ϕ = angle between the magnet moment and the field (^{o}).

In 1987 at FERMI Lab's Fifteen-Foot Bubble Chamber, tests were performed on a wrench, nail, pen, clipboard, and safety shoes. The tests showed some interference at 30 mT (300 G), with significant interference at 60 mT (600 G) (these levels are compatible to the whole body 8-hour time-weighted average limit from the ACGIH). Rotational forces make normal handling of ferromagnetic objects almost impossible at 200 mT (2,000 G) field levels.

Translational Force

The translational magnetic force can be calculated from the gradient of the change in the magnetic field energy density resulting from the presence of the ferromagnetic object in the magnetic field.

$$F_{mag} = \nabla\left[(U - U_o)V\right]$$

Where F_{mag} = magnetic force on the ferromagnetic object (N)
∇ = gradient operator
U = energy density with ferromagnetic object (J/m^3)
U_o = energy density without ferromagnetic object (J/m^3)
V = volume of ferromagnetic object (m^3).

The magnetic field energy density is given by:

$$U = \frac{1}{2}\vec{B}\cdot\vec{H}$$

Where B = magnetic flux density (T)
H = magnetic field density (A/m).

The magnetic flux density in the absence of the ferromagnetic object is:

$$\vec{B}_o = \mu_o\vec{H}$$

Where μ_o = permeability of free space = $4\pi \times 10^{-7}$ H/m.

The internal flux density of a ferromagnetic object is:

$$\vec{B}_o = \mu_{eff}\mu_o\vec{H}$$

Where μ_{eff} = effective permeability of the ferromagnetic material after correction for demagnetization.

The value of μ_{eff} is dependent on the material and shape and can vary greatly (i.e., a long thin soft iron rod can have an μ_{eff} 1,000 times greater than that of a sphere of the same material). If it is assumed that the ferromagnetic object is spherical (since other geometries are incredibly complicated), the internal magnetic flux density is:

$$\vec{B}_o = 3\mu_o \vec{H}$$

i.e., $\mu_{eff} = 3$ for a sphere made of any ferromagnetic material.

Therefore, the magnetic force is approximately

$$F_{mag} = \nabla\{[\frac{1}{2}(3\mu_o \vec{H}\cdot\vec{H}) - \frac{1}{2}(\mu_o \vec{H}\cdot\vec{H})]V\}$$

$$F_{mag} = \nabla(\mu_o H^2 V) = \nabla(\frac{V}{\mu_o} B_o^2)$$

$$F_{mag} = \frac{2V}{\mu_o} B_o \frac{dB_o}{dr}$$

It is now possible to determine the field conditions that will result in the translational magnetic force that can be expected to interfere with normal handling. We will assume this occurs when the translational force is equal to one-tenth the force due to gravity. In addition, we will assume that the object is an iron sphere.

$$F_{mag} = 0.1 F_{gravity}$$

$$\frac{2V}{\mu_o} B_o \frac{dB_o}{dr} = 0.1\rho V g$$

$$B_o \frac{dB_o}{dr} = \frac{0.1\mu_o r g}{2} = \frac{(0.1)(4\pi\times10^{-7}\frac{H}{m})(7900\frac{kg}{m^3})(9.8\frac{m}{s^2})}{2}$$

$$B_o \frac{dB_o}{dr} = 4.9\times10^{-3}\frac{T^2}{m} = 4.9\times10^{3}\frac{G^2}{cm}$$

Limited measurements made in 1987 *suggest* that translational forces may be "noticeable" above 10^{-4} T^2/m (10^2 G^2/cm) and equal to the gravitational force above 10^{-3} T^2/m (10^3 G^2/cm). However, a subset of the observations indicates that much higher values – up to 100 times – are needed to produce problematical translational forces.